AFRL-RQ-WP-TM-2013-0072

ENERGY-BASED DESIGN OF RECONFIGURABLE MICRO AERIAL VEHICLE (MAV) FLIGHT STRUCTURES

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Interim Report

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14. ABSTRACT
The objective of the project is to understand how to mechanize multi-jointed MAV wings for perching and/or flapping applications and develop an energy-based design framework for the solution of combined multi-physics, multi-objective problems.

15. SUBJECT TERMS
micro air vehicle, perching, topology optimization

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Energy-Based Design of Reconfigurable MAV Flight Structures

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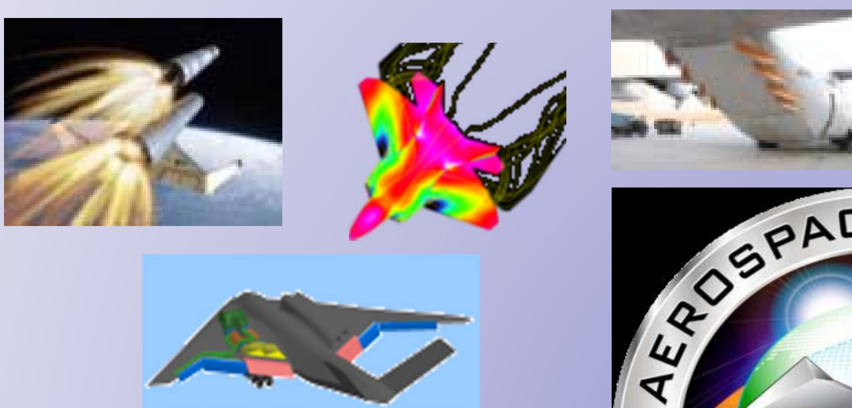
RQ Tech Division Consolidation

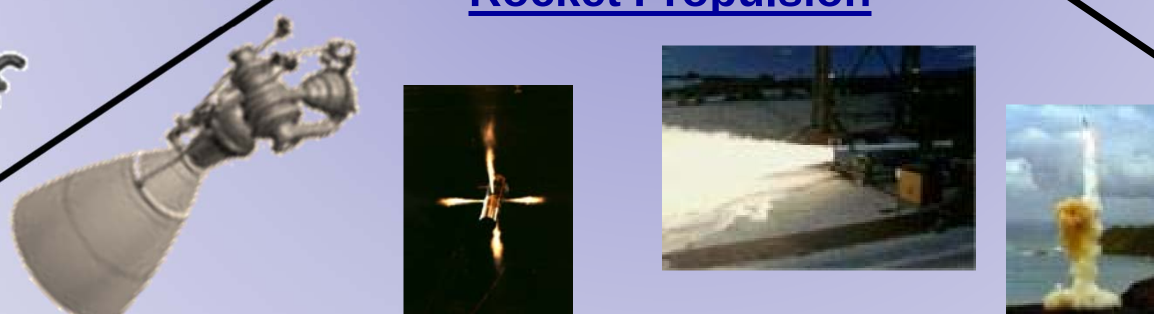
Aerospace Vehicles



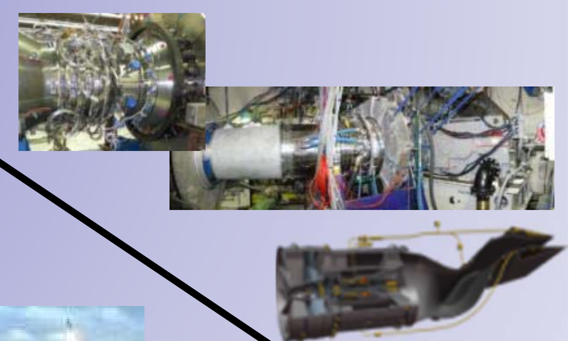
High Speed Systems

Power and Control

Rocket Propulsion

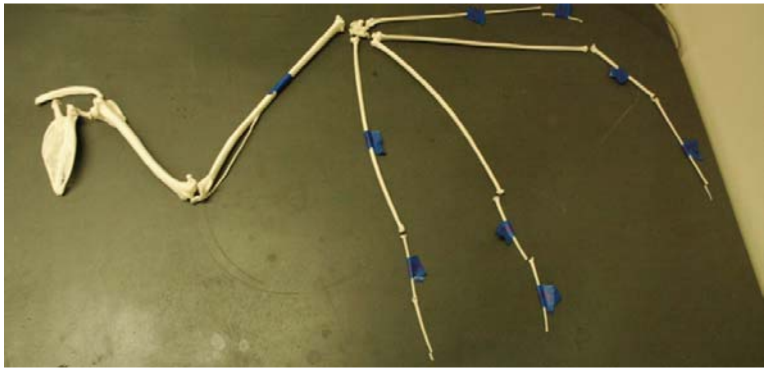


Turbine Engine



Motivation

- Biological systems not necessarily designed for optimal flight
- Engineered systems don't have requirements related to feeding, care for young, etc.
- Should we be attempting to mimic natural systems, knowing that they are not optimized for flight?
- What would a biological system look like if optimized only for flight?
- Can we use engineering design and optimization to create a "flight-only estimate" of the biological system?



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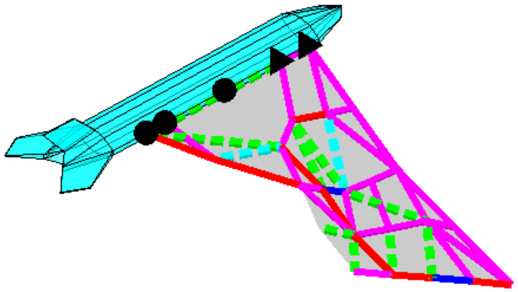
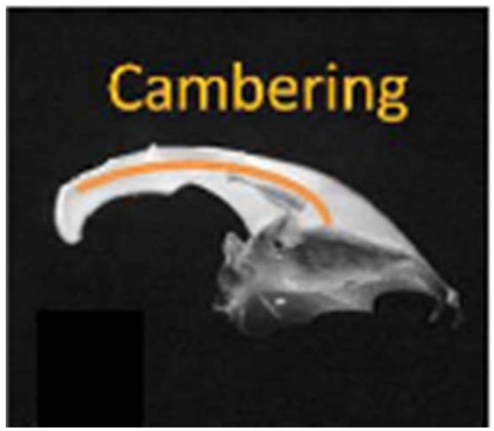
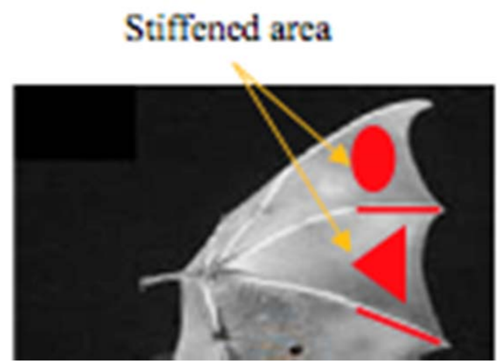


Objective

- **Understand how to mechanize multi-jointed MAV wings for perching and/or flapping applications**
- **Develop an energy-based design framework for the solution of combined multi-physics, multi-objective problems**



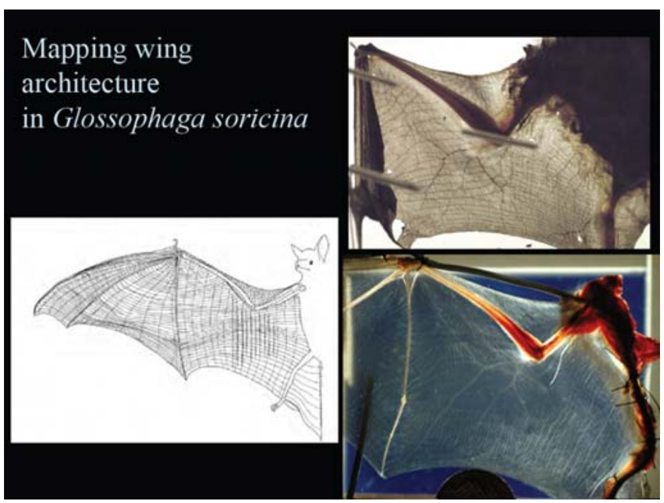


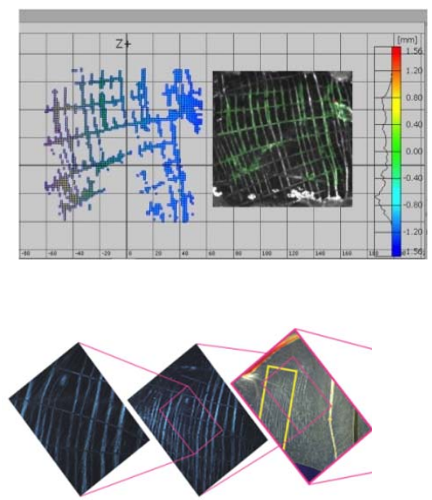
Technical Challenges

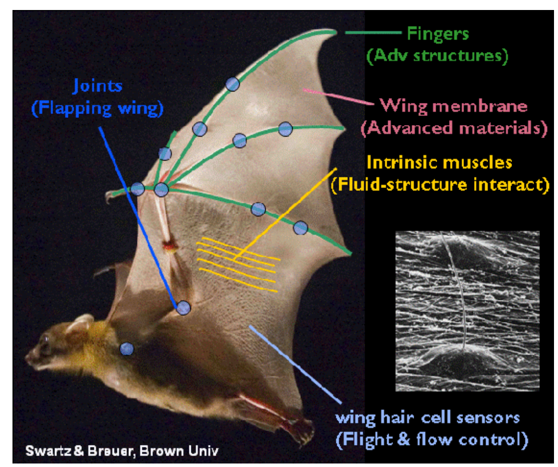
- **Design tool for multi-physics analysis and optimization under unsteady aerodynamic load is not well established**
- **Identification of wing morphology requirements is not well understood**
- **Performance measures such as energy and efficiency measures for unsteady aerodynamic flight are not well defined**
- **Passive shape control to maximize energy efficiency is not well exploited**

Approach

- **Student 1 (AFIT) will focus on the distribution of skin material to meet performance objectives after selecting four snap shots of a bird wing configuration during perch**
- **Student 2 (UD) will extend the scope of the research to include active shape control (mechanism synthesis) in addition to skin material distribution**

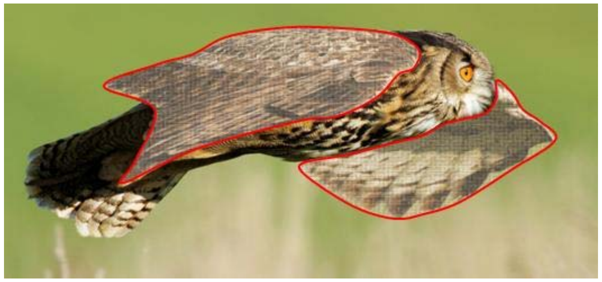




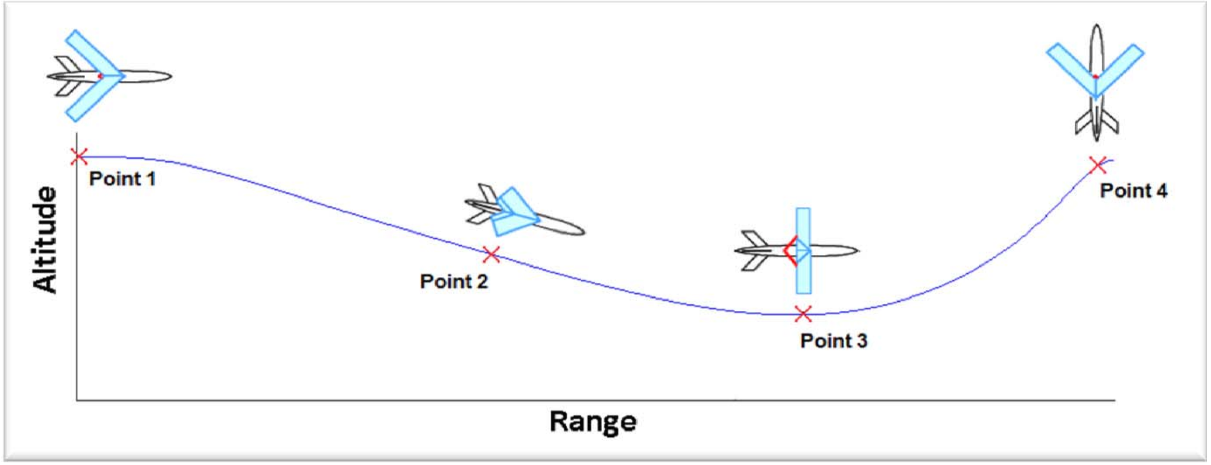


Wing Skin Structure Design

- **Configuration Selection**



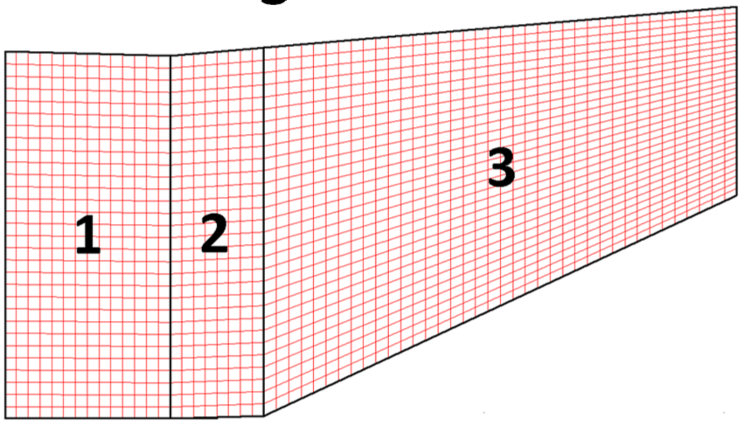
Eagle Owl in Loiter, Dash, and Flare Configurations



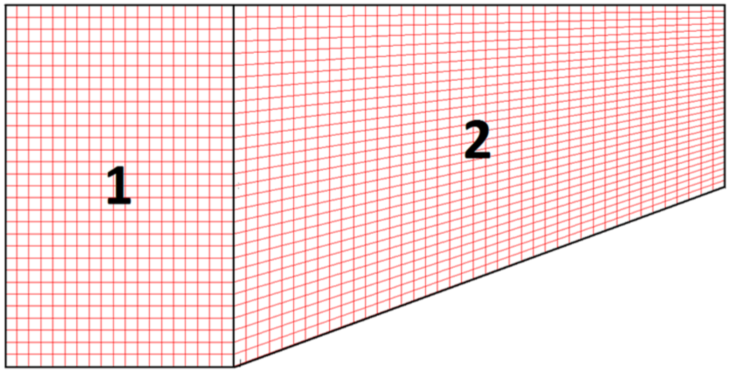
Typical Perching Trajectory and Perching Wing Configurations

Wing Skin Structure Design

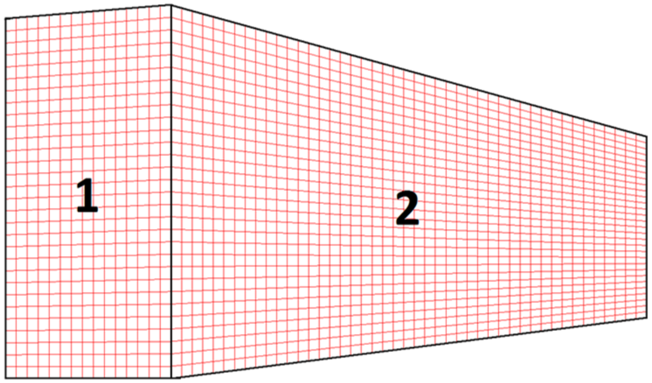
- **Configuration Selection**



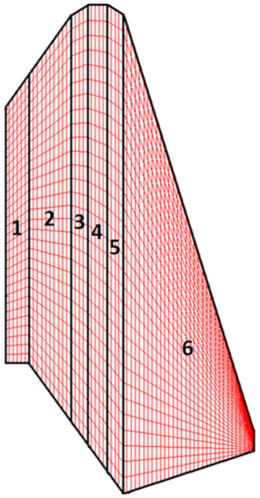
Forward Swept Configuration



Zero Sweep Configuration



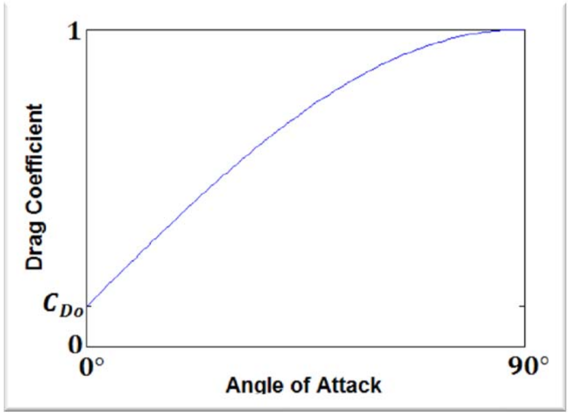
Back Swept Configuration



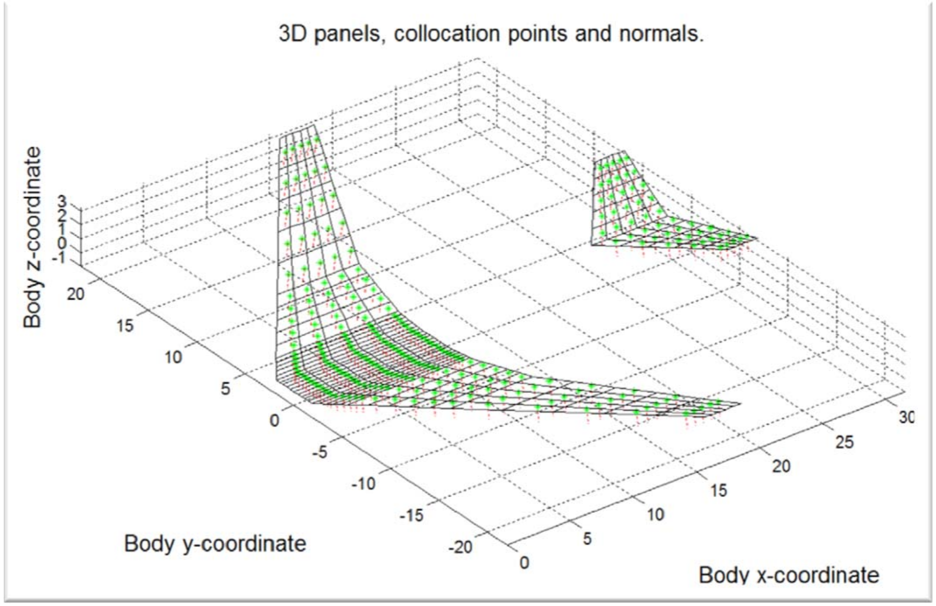
Dive Configuration

Wing Skin Structure Design

- **Force Estimation**
  - Forces were calculated in MATLAB Vortex Lattice code called **Tornado**
  - *Zero-lift, flat-plate drag coefficient* estimated by Tornado
  - Drag coefficient related to angle of attack
  - Force on each panel split into four components and applied to the nodes



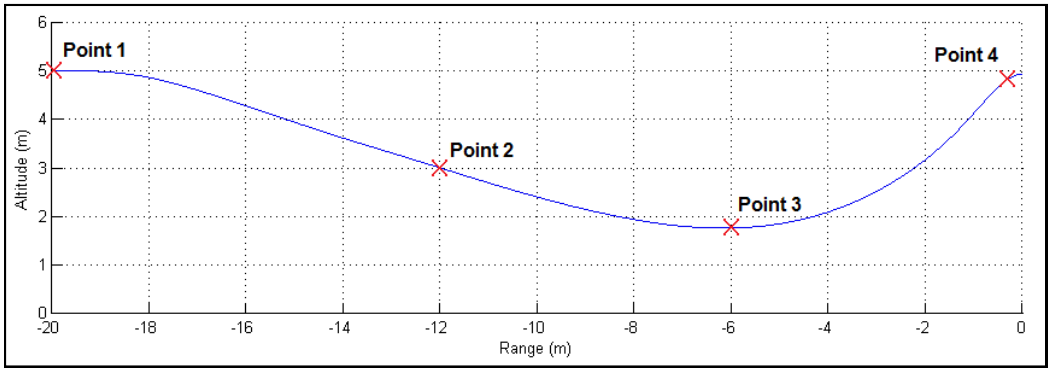
Viscous Drag Estimation Curve



Example of Tornado Vortex Panels Output

Wing Skin Structure Design

- **Perching Data**



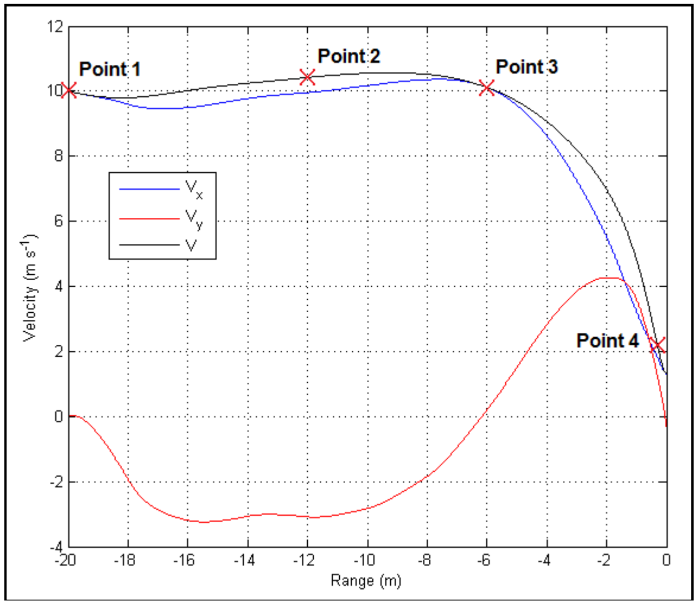
Wing Configuration:

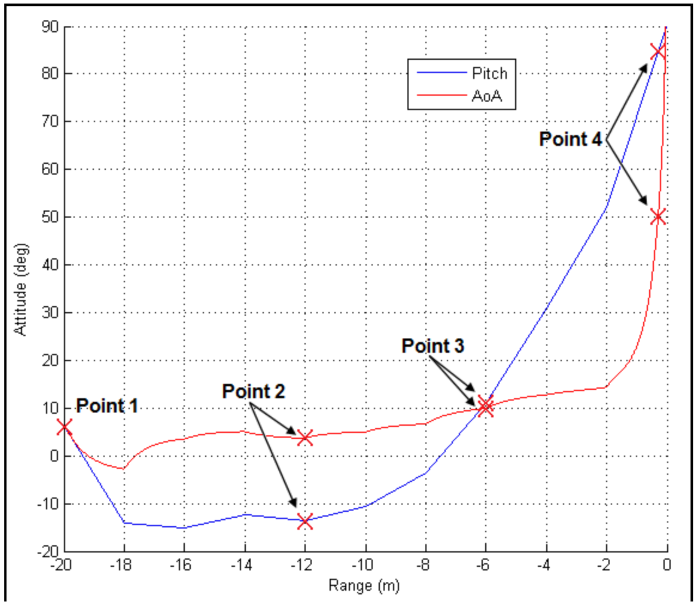
Point 1: Back Swept

Point 2: Dive

Point 3: Zero Sweep

Point 4: Forward Swept





Wing Skin Structure Design

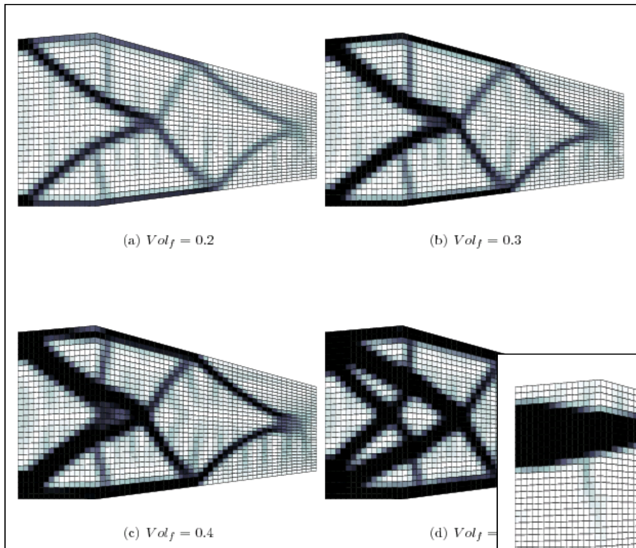
- **Force Estimation**
  - Induced drag is highest for Point 3, not Point 4, and lowest at Point 2
  - Side forces have minimal influence on resulting topologies
  - Lift highest for Point 3
  - Axial body force pushes wing forward
  - Most bending loads about 10 times the membrane loads
  - Viscous drag is lowest at Point 4, even though the Point 4 is at a high angle of attack

Aerodynamic Data for Birdwing Along Perching Trajectory

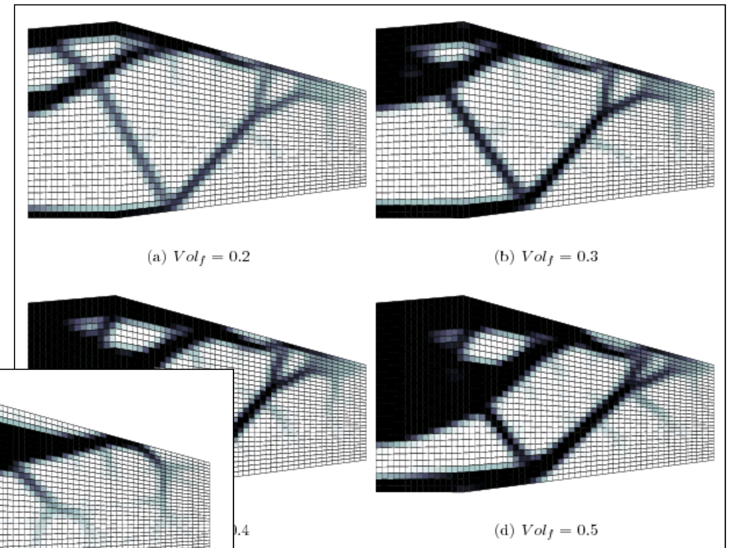
		Point 1	Point 2	Point 3	Point 4
$Vel.$	[m/s]	10	10.41	10.11	2.19
AOA	[°]	6	3.75	10	50
$Drag$	[N]	0.0176	0.0033	0.0796	0.0456
$Side$	[N]	0.0061	0.0075	-0.0007	-0.0087
$Lift$	[N]	0.459	0.112	1.241	0.196
F_x	[N]	-0.0304	-0.0040	-0.1371	-0.1208
F_y	[N]	0.00610	0.00749	-0.00066	-0.00871
F_z	[N]	0.458	0.112	1.236	0.161
C_L	[—]	0.220	0.076	0.512	1.701
C_D	[—]	0.0085	0.0022	0.0328	0.3958
C_Y	[—]	0.0029	0.0051	-0.0003	-0.0757
R_e	[—]	90054	137712	91412	19987
C_{Do}	[—]	0.0101	0.0082	0.0101	0.0113
S_{wet}	$[m^2]$	0.0681	0.0444	0.0775	0.0785
D_{vis}	[N]	0.2368	0.1077	0.4410	0.0885
$Normal$	[N]	0.0248	0.0070	0.0766	0.0678
$Axial$	[N]	0.2355	0.1075	0.4343	0.0569

Wing Skin Structure Design

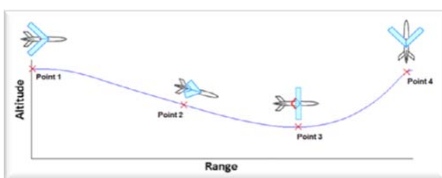
- **Results – Point 1**

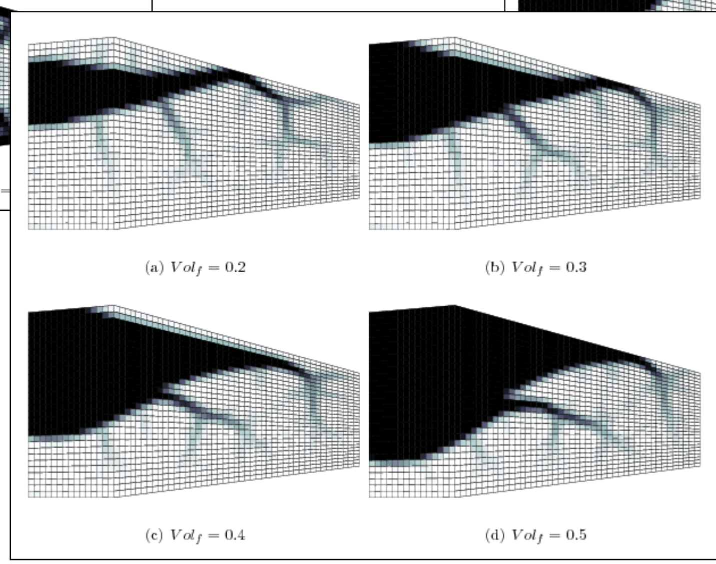


Membrane



Bending

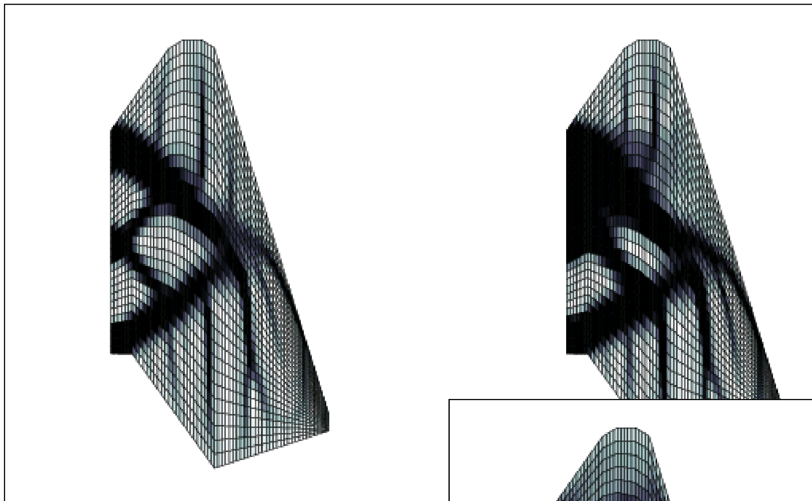




Combined

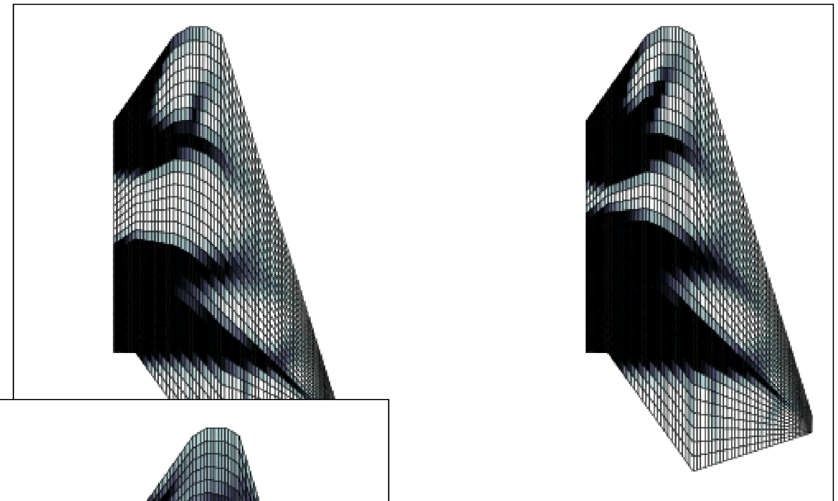
Wing Skin Structure Design

- **Results – Point 2**



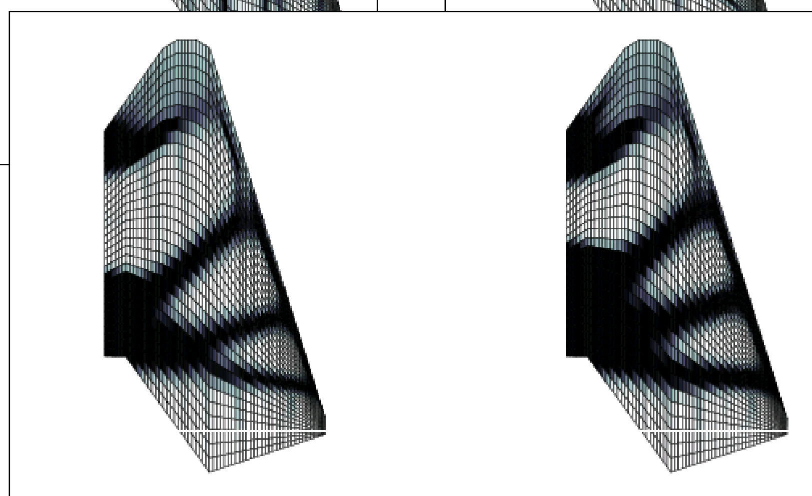
(c) $Vol_f = 0.4$

Membrane



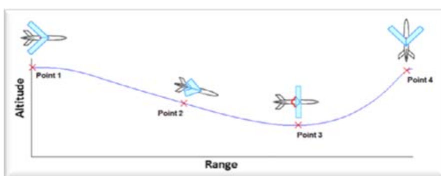
(b) $Vol_f = 0.5$

Bending



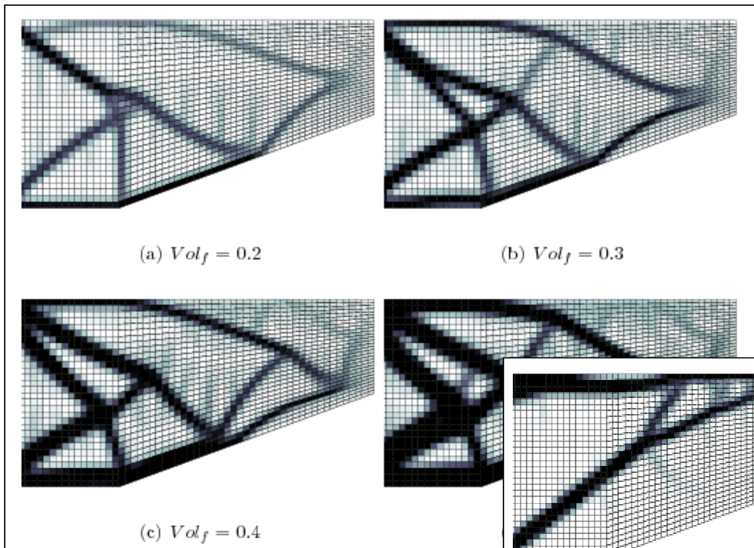
(c) $Vol_f = 0.4$ (d) $Vol_f = 0.5$

Combined

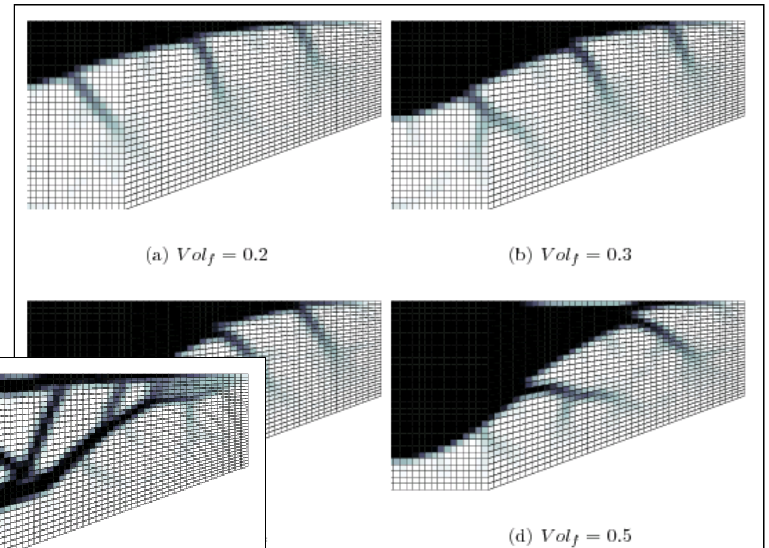


Wing Skin Structure Design

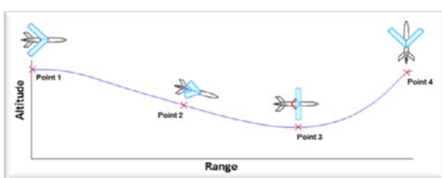
- **Results – Point 3**

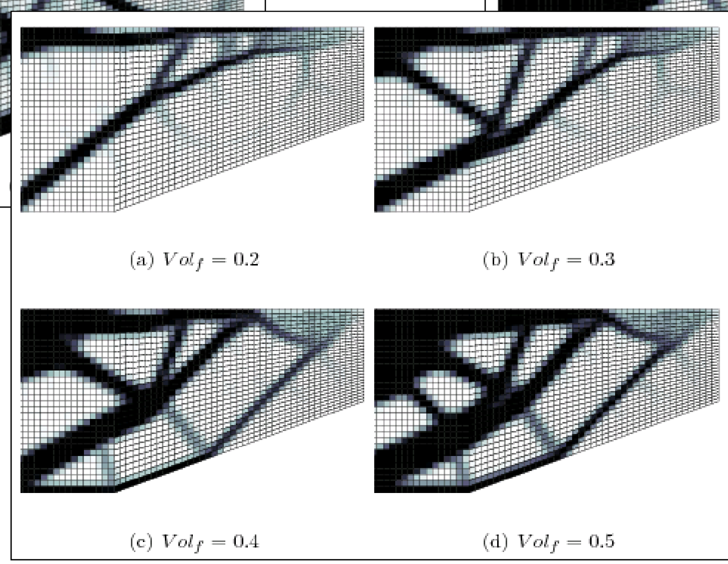


Membrane



Bending

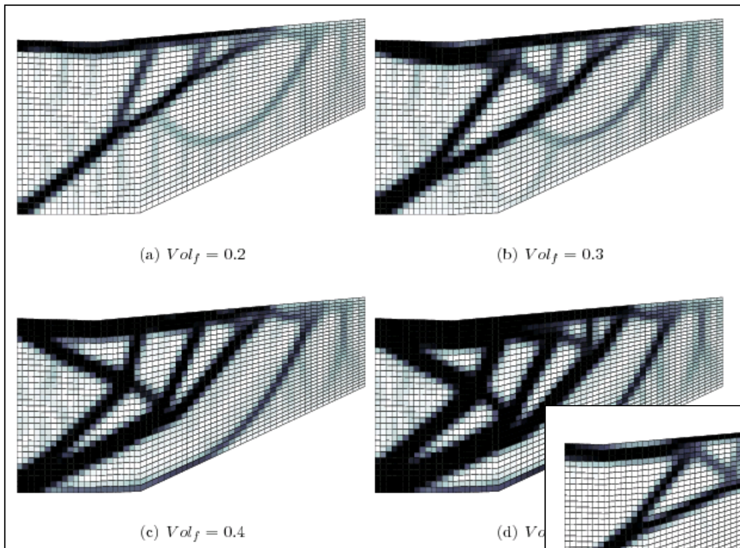




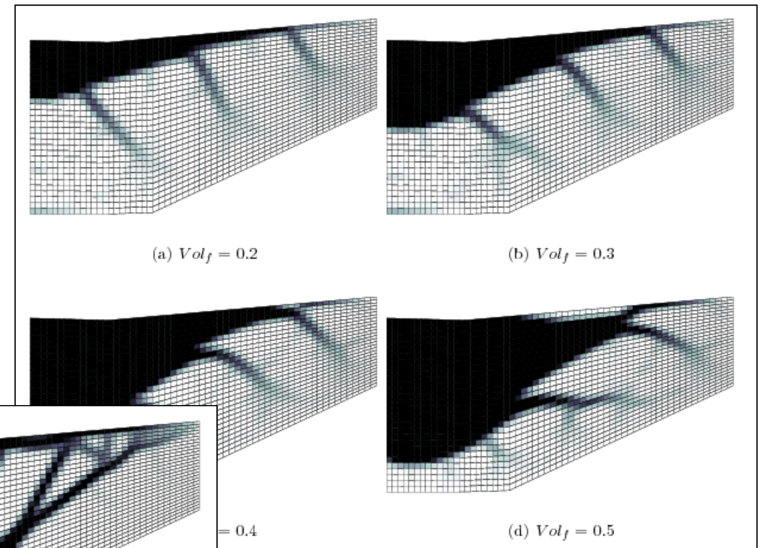
Combined

Wing Skin Structure Design

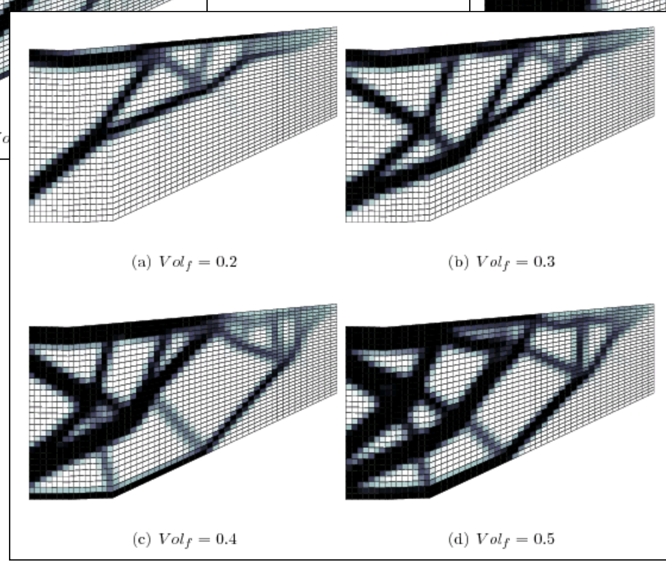
- **Results – Point 4**



Membrane



Bending



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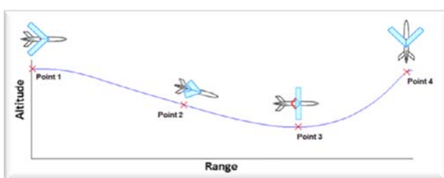
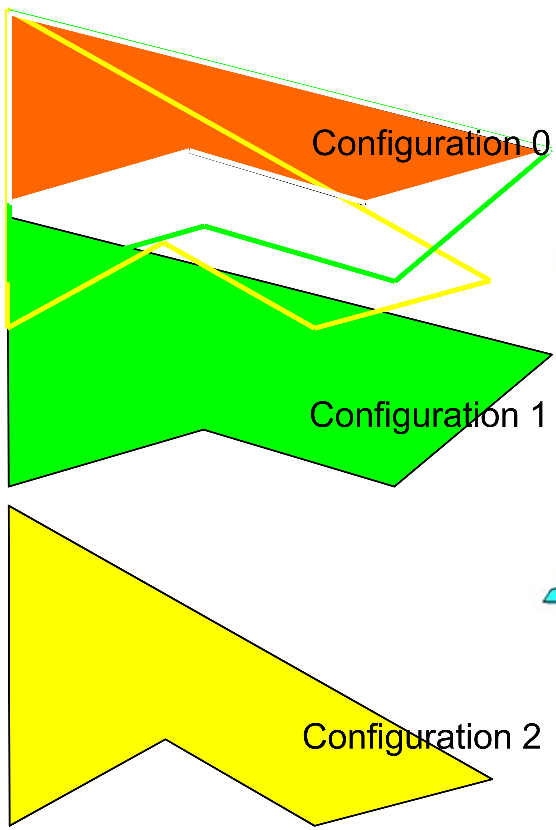


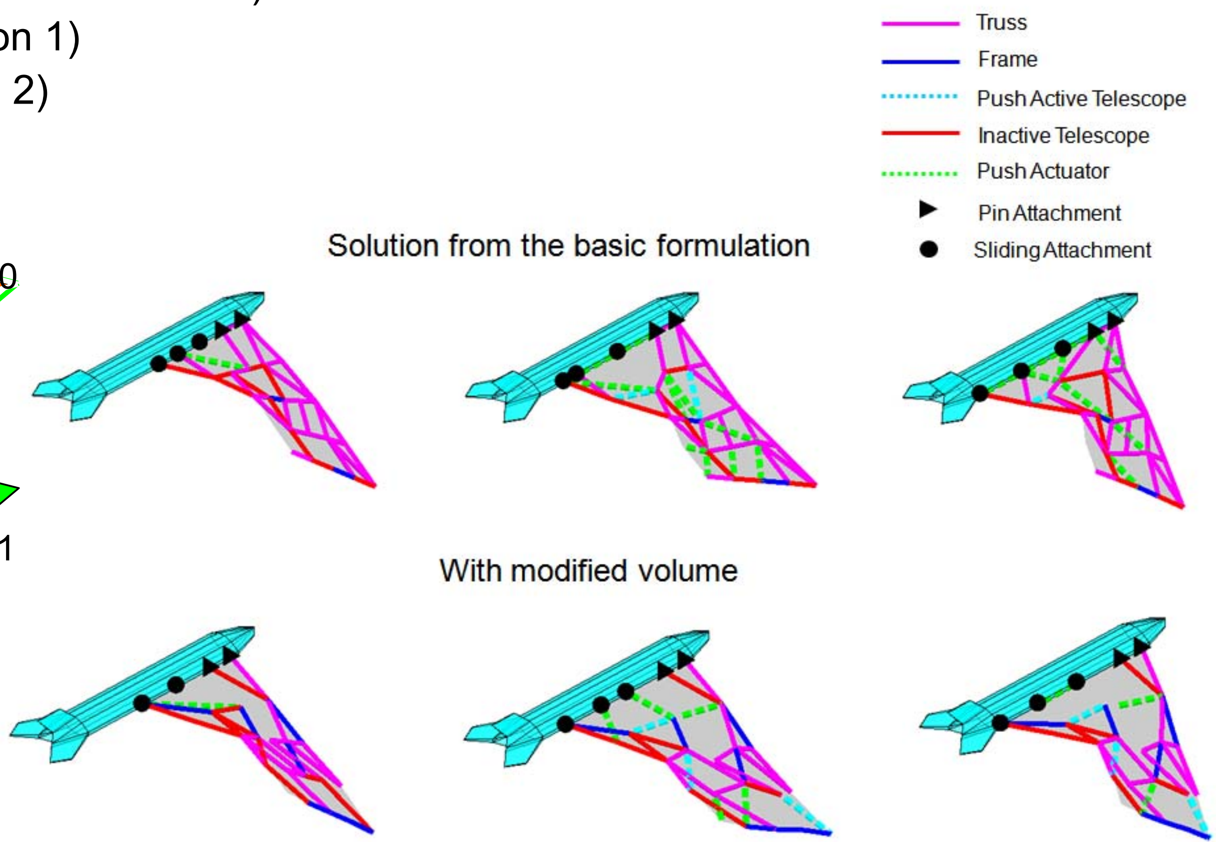
Wing Skin Structure Design

- **Summary**
  - In general, structural members support the leading edge
  - Membrane solutions resemble truss-like structures, and bending solutions resemble beam-like structures
  - Membrane solutions clearly dominate the combined loading
  - When the viscous drag distributed over the surface of the wing is not considered, hybrid solutions occur
  - Secondary features include straight battens in membrane structures, and branches in bending structures
  - Membrane solution must support out-of-plane loading, so discrete “truss” members must function like spars
  - The topology constantly changes at different points along perching trajectory so we need an active mechanism to reconfigure at different loading conditions → Wing mechanism design

Previous Research (Multiple Configurations)

- Generic Surveillance UAV with three configurations
  - Loiter (configuration 0 = reference)
  - High lift (configuration 1)
  - Climb (configuration 2)



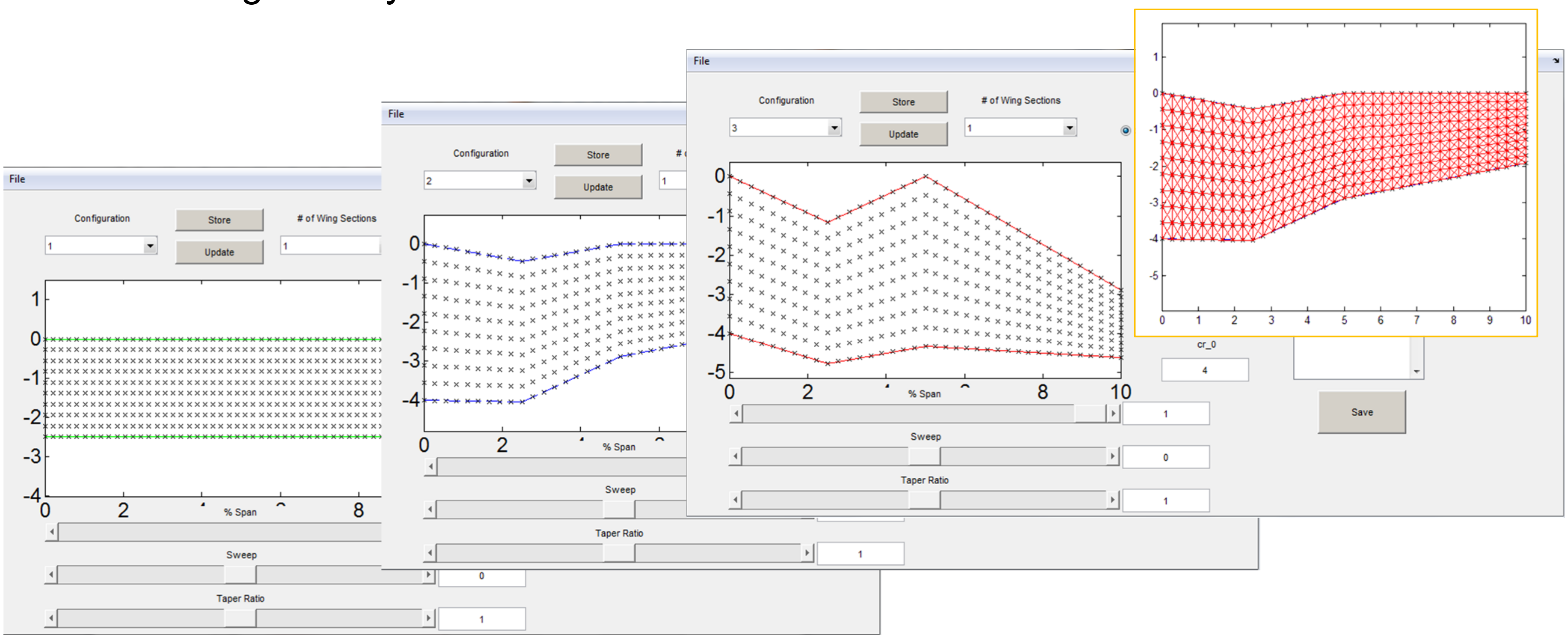


Wing Mechanism Design

- **Developing design tool for energy-based optimization of structure topology**
- **Currently includes…**
  – Geometry Generator
  – Pre-Processor
  – Structural Analysis
  – Optimization Routine
  – Aerodynamic Analysis (in progress)
  – Post-Processor (in progress)

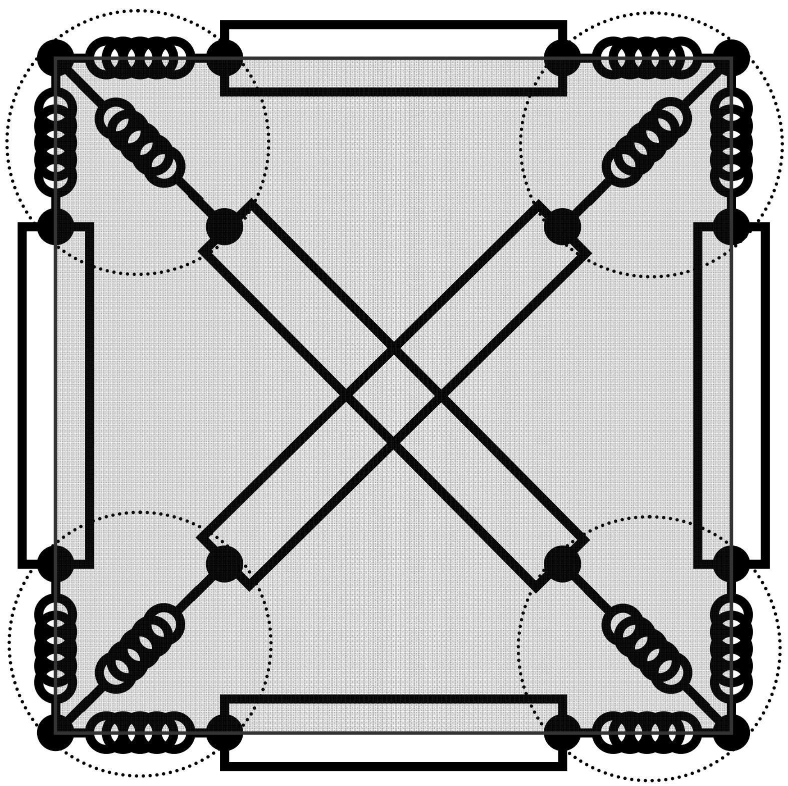
Wing Mechanism Design

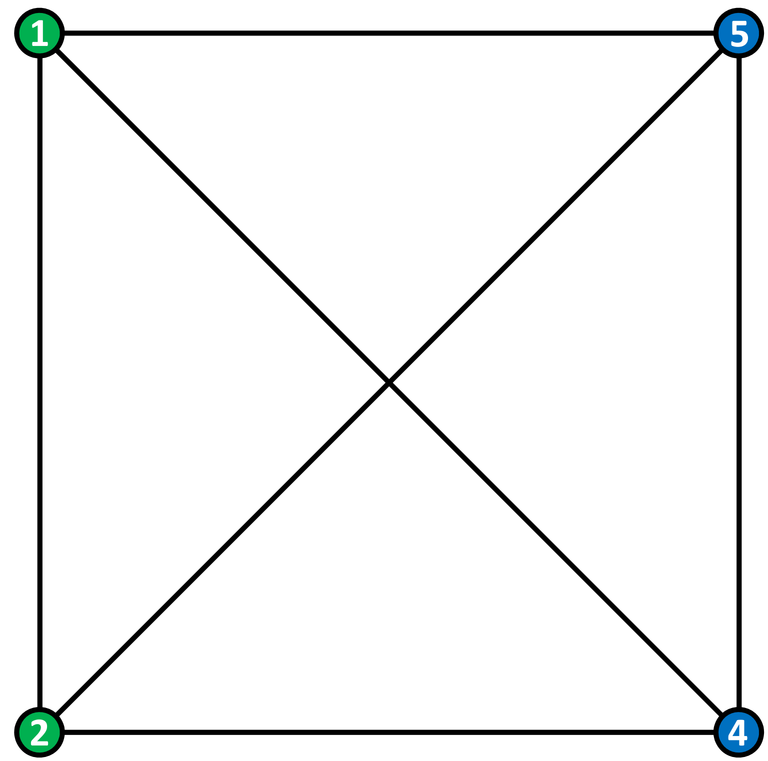
- **Geometry Generator/Preprocessor**
  - Includes a GUI for ease of use
  - Creates a parametrically defined wing geometry
    - Facilitates future optimization routines that could update body geometry



Wing Mechanism Design

- **Box Substructure Description**

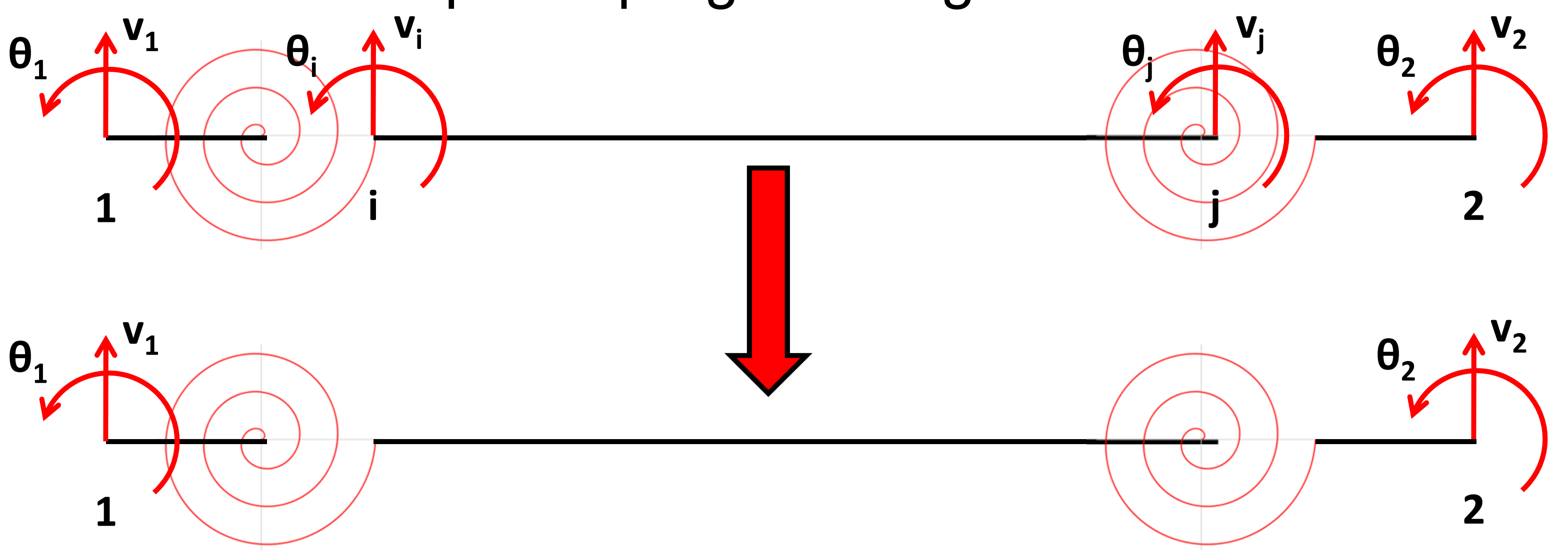




16 Nodes → **4 Nodes**

Wing Mechanism Design

- **Structural Analysis**
  - Implements Standard finite element approach
  - Uses a condensed frame element with rotational springs on each end
  - Reduces DoFs thereby decreasing computational time and simplifies programming



Wing Mechanism Design

- **Optimization Routine**
  - Globally Convergent Method of Moving Asymptotes
    - Developed by Svanberg
    - One of the most used methods for structural optimization
  - Problem Formulation
    - Minimize:
      - Shape Error and Actuator Usage
    - Subject to:
      - Static Equilibrium
      - Stroke Limit
      - Attachment Stiffness
      - +/- Volume Fraction

Minimize:

$$f_0 = W_1 \sum_{i \in T} (U_i^{target} - U(\rho)_i)^2 + W_2 \sum_{i \in A} \rho_j^2$$

Subject to:

$$f_{eq} = KU - F = 0 \qquad \textit{Static Equilibrum}$$
$$f_m = E_m^2 - E_{max}^2 \leq 0 \qquad \textit{Stroke Limt}$$
$$f_F = \sum_{i \in B} \rho_i - N_F \leq 0 \qquad \textit{Attachment Placement Limit}$$
$$f_{+V} = \sum_{i \in L1} \rho_i + \sum_{i \in L2} \rho - V_{max} \leq 0 \qquad \textit{Volume Fraction Limit}$$
$$f_{-V} = -\sum_{i \in L1} \rho_i - \sum_{i \in L2} \rho + V_{min} \leq 0 \qquad \textit{Volume Fraction Limit}$$

Wing Mechanism Design

- **Aerodynamic Analysis (in progress)**
  - Extracting Aerodynamic Influence Coefficient (AIC) matrix from Tornado for use in a static aeroelastic analysis
  - Coupling aerodynamic loads and structural deformation
  - Leveraging the aeroelastic deformation, it is assumed a reduced use in energy design may be found
- **Post- Processor**
  - Clearly displays the results from the design tool

Research Plans for Next FY

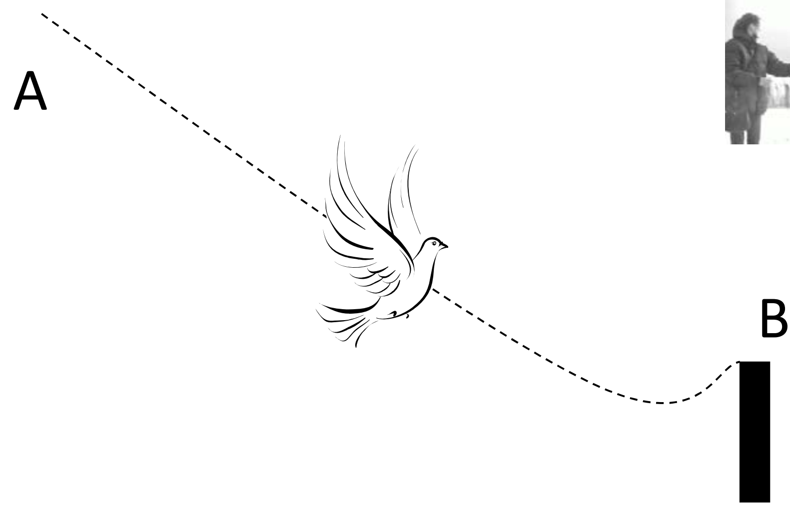
- **Key energy metrics and efficiency measures for optimal multi-physics designs**
- **Design methodology to determine passive and active shape control for efficient vehicle flight performance**
- **Comparison of engineering and evolutionary optimal solutions for similar systems**

Backup

Approach

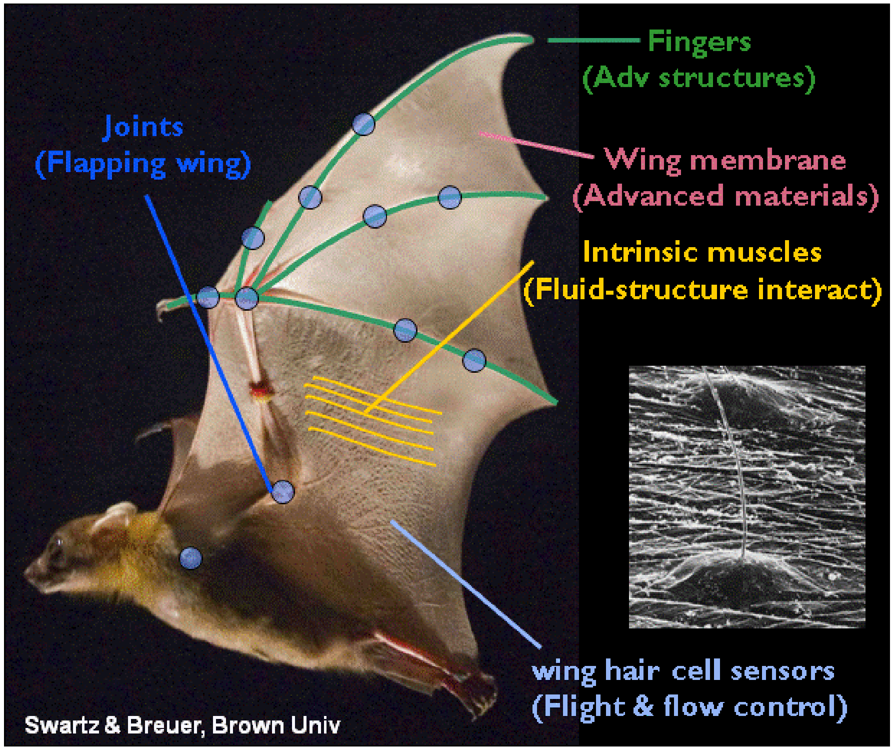
- **Utilize design optimization techniques for efficient design of aeroelastic reconfigurable systems incorporating distributed actuation and compliance**
- **Develop flight energy and efficiency measures for topology optimization**
- **Provide understanding of a systematic design process for a bio-mimetic vehicle design problem**

- **Select “snapshots” of vehicle in perching maneuver at different times**
- **Optimize based on multiple load conditions**
- **Identify suitable objective functions to produce “good” designs**



Approach

- **Student 2 (UD) will extend the scope of the research to include mechanism design scheme in addition to skin material distribution**



Wing Skin Structure Design

- **Optimality Criteria Method**
  - OC method is a bisection method based on the fact that the material volume is a monotonically decreasing function of the Lagrange multiplier
  - Stationarity point is achieved when volume constraint is satisfied
  - Update scheme given by:

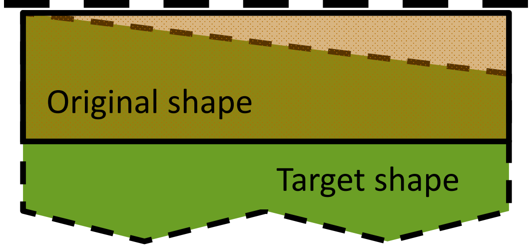
$$\rho_e^{k+1} = \min\left\{ \max\left[\rho_e^k \left(\frac{q\rho_e^{q-1}(\boldsymbol{d}_e^k)^T \boldsymbol{k}_e^T \boldsymbol{d}_e^k}{\lambda a_e} \right)^\eta, \rho_{min} \right], \rho_{max} \right\}$$

such that the volume constraint satisfies

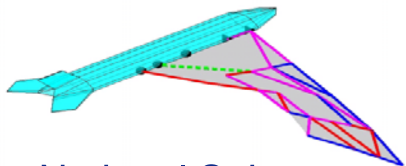
$$\sum_{e=1}^{N} a_e \rho_e^{k+1}(\lambda) - V = 0$$

  - OC method closely related to fully stressed design, where all elements have same strain energy; not exactly the case, because of SIMP model

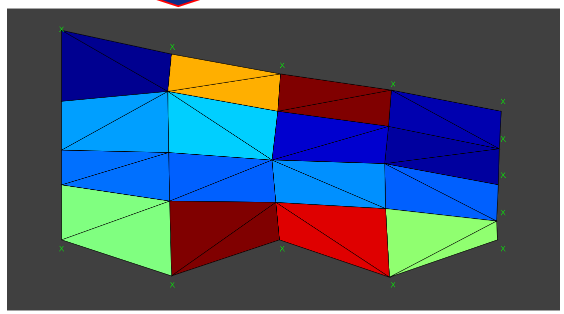
Previous Research (Flexible Skin Design)



Example Target Shapes



Notional Substructure



- Two-step topology optimization process
  - Step 1: distribution of bulk material properties
  - Step 2: distribution of multi-phase material

(1)

$$Q^{*}=\begin{bmatrix}1.6979 & 0.6230 & 0\\ 0.6230 & 1.8880 & 0\\ 0 & 0 & 0.5066\end{bmatrix}\times 1e^{3}$$

Target Reduced Stiffness Matrix

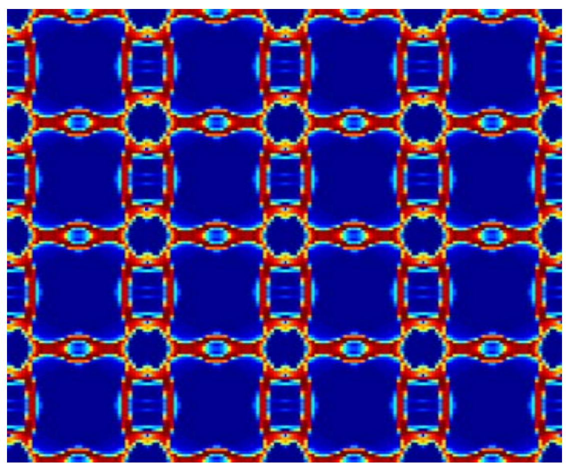
(2)

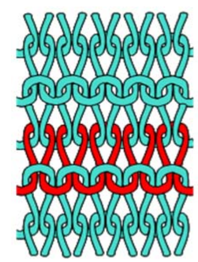
$$Q^{H}=\begin{bmatrix}1.7179 & 0.6076 & 0\\ 0.6076 & 1.9021 & 0\\ 0 & 0 & 0.5184\end{bmatrix}\times 1e^{3}$$

Reduced Stiffness Matrix from Homogenization Routine

$$p_E \Rightarrow$$
$$E^{e}_{ijkl}\left(p_E\right)=p_E^{\beta}E^{1}_{ijkl}+\left(1-p_E^{\beta}\right)E^{2}_{ijkl}$$

Two Phase Material Solution





Ad Hoc Solution

Turning Theory Into Application
Reducing Design Time

Wing Skin Structure Design

- **Finite Element Derivation**
  - Membrane Element
  - Bending Element
  - Combined Membrane/Bending Element

Superimposed membrane and bending plate models to form 6-dof model

$$\left\{\begin{array}{c}\underset{8\ x\ 1}{\{f_m\}} \\ \hline \underset{12\ x\ 1}{\{f_b\}} \\ \hline \underset{4\ x\ 1}{\{f_{\theta z}\}}\end{array}\right\} = \left[\begin{array}{cc|c}\underset{8\ x\ 8}{[k_m]} & \underset{8\ x\ 12}{[0]} & \\ \underset{12\ x\ 8}{[0]} & \underset{12\ x\ 12}{[k_b]} & \underset{20\ x\ 4}{[0]} \\ \hline \multicolumn{2}{c|}{\underset{4\ x\ 20}{[0]}} & \underset{4\ x\ 4}{[0]}\end{array}\right] \left\{\begin{array}{c}\underset{8\ x\ 1}{\{d_m\}} \\ \hline \underset{12\ x\ 1}{\{d_b\}} \\ \hline \underset{4\ x\ 1}{\{d_{\theta z}\}}\end{array}\right\}$$

Fictitious stiffness matrix added for "drilling" degrees of freedom to avoid singularities

$$\begin{Bmatrix} M_{z1} \\ M_{z2} \\ M_{z3} \\ M_{z4} \end{Bmatrix} = \alpha EV \begin{bmatrix} 1.0 & -0.5 & -0.5 & -0.5 \\ -0.5 & 1.0 & -0.5 & -0.5 \\ -0.5 & -0.5 & 1.0 & -0.5 \\ -0.5 & -0.5 & -0.5 & 1.0 \end{bmatrix} \begin{Bmatrix} \theta_{z1} \\ \theta_{z2} \\ \theta_{z3} \\ \theta_{z4} \end{Bmatrix}$$

Wing Skin Structure Design

- **Topology Optimization**
  - Minimizing compliance equivalent to maximizing stiffness
  - Compliance is equivalent to the strain energy of a deformed structure
  - Volume constraint is added to avoid infinite stiffness
  - Nested compliance minimization optimization statement:

$$\min_{\boldsymbol{\rho}} \; c(\boldsymbol{\rho})$$

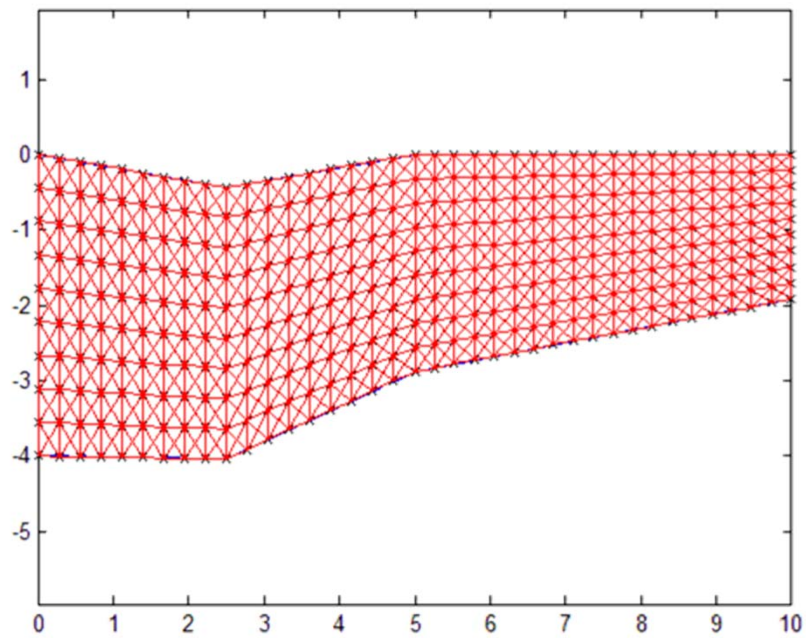
$$\text{s.t.} \;\; \{\rho\}^T\{a\} - V = 0, \quad 0 < \rho_{min} \leq \rho_e \leq \rho_{max}, \qquad e = 1, \ldots, N$$

where the compliance *c* is defined by

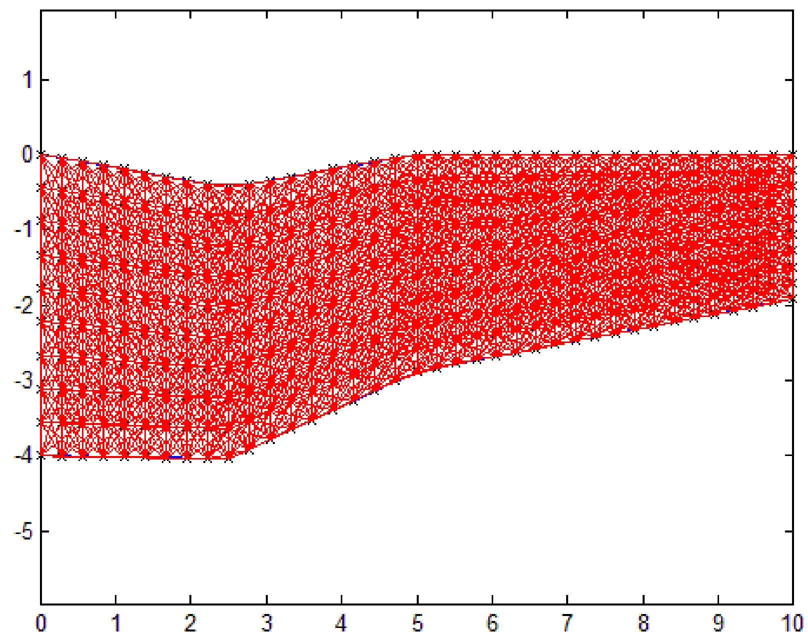
$$c(\boldsymbol{\rho}) = \{F\}^T\{d\}, \qquad \text{where } \{d\} \text{ solves:} \qquad \left(\sum_{e=1}^{N}[k_e]\right)\{d\} = \{F\}$$

Wing Mechanism Design

- **Geometry Generator/Preprocessor**
  - Generates varying degrees of mesh connectivity for the initial ground structure topology



Degree of Connectivity = 1

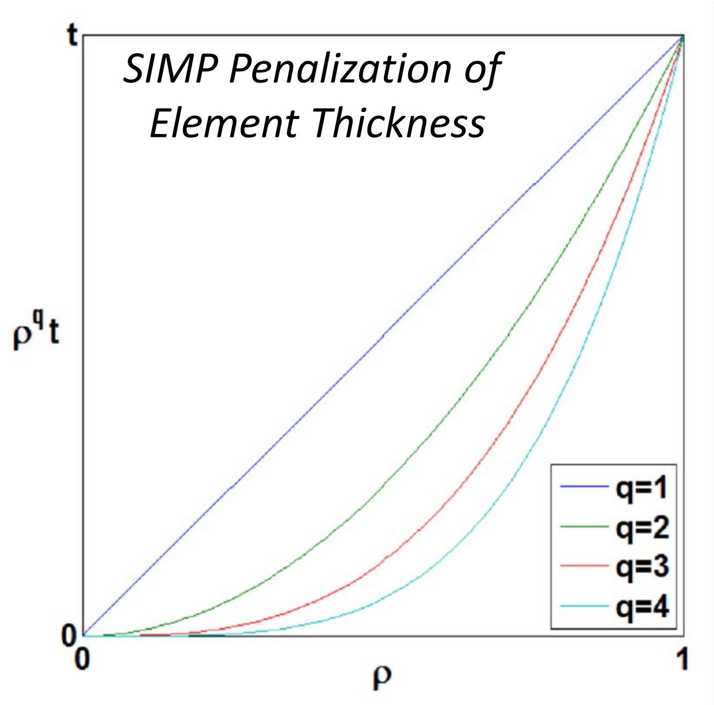


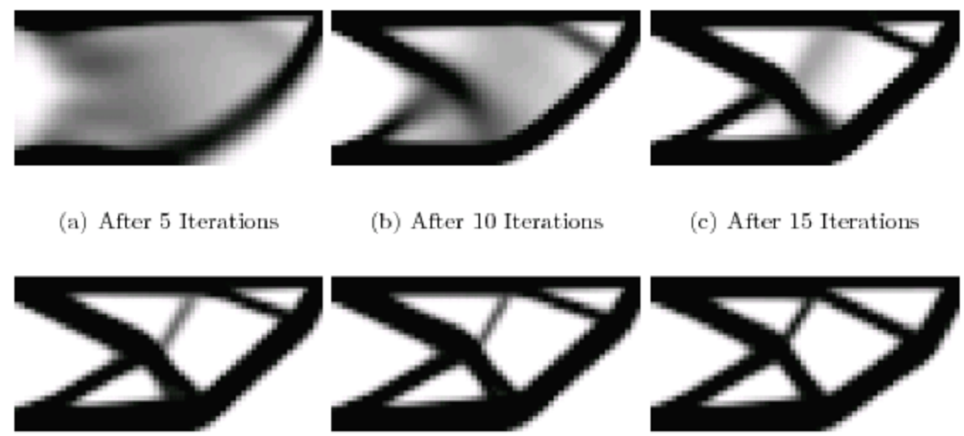
Degree of Connectivity = 2

Wing Skin Structure Design

- **Solid Isotropic Material with Penalization (SIMP)**
  - Penalizes intermediate thickness values, driving thicknesses towards a discrete solution
  - Thicknesses are penalized by raising the element thickness to a power greater than 1 in the constitutive matrix:

$$[D] = \frac{\rho^q E t}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix}$$





(a) After 5 Iterations (b) After 10 Iterations (c) After 15 Iterations

(d) After 20 Iterations (e) After 50 Iterations (f) After 298 Iterations